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DEVELOPMENTS IN REDES: THE ROCKET ENGINE DESIGN EXPERT SYSTEM

Kenneth O. Davidian

National Aeronautics and Space Administration

Lewis Research Center

Cleveland, Ohio 44135-3191

ABSTRACT

The Rocket Engine Design Expert System (REDES) is being developed at the NASA Lewis Research Center to collect, automate, and perpetuate the existing expertise of performing a comprehensive rocket engine analysis and design. Currently, REDES uses the rigorous JANNAF methodology to analyze the performance of the thrust chamber and perform computational studies of liquid rocket engine problems. The following computer codes have been included in REDES: a gas properties program named GASP, a nozzle design program named RAO, a regenerative cooling channel performance evaluation code named RTE, and the JANNAF standard liquid rocket engine performance prediction code TDK (including performance evaluation modules ODE, ODK, TDE, TDK, and BLM). Computational analyses are being conducted by REDES to provide solutions to liquid rocket engine thrust chamber problems. REDES is built in the Knowledge Engineering Environment (KEE) expert system shell and runs on a Sun 4/110 computer.

INTRODUCTION

Many domains of expertise are required for the complex task of analyzing and designing a liquid rocket engine thrust chamber (figure 1). Presently, this expertise is possessed by individuals who, when assembled and organized, constitute a "design team." Experts in each technical field must interact with each other, iterating between intermediate solutions, to arrive at a final design.

Figure 1. Many domains of expertise are required to design a thrust chamber.

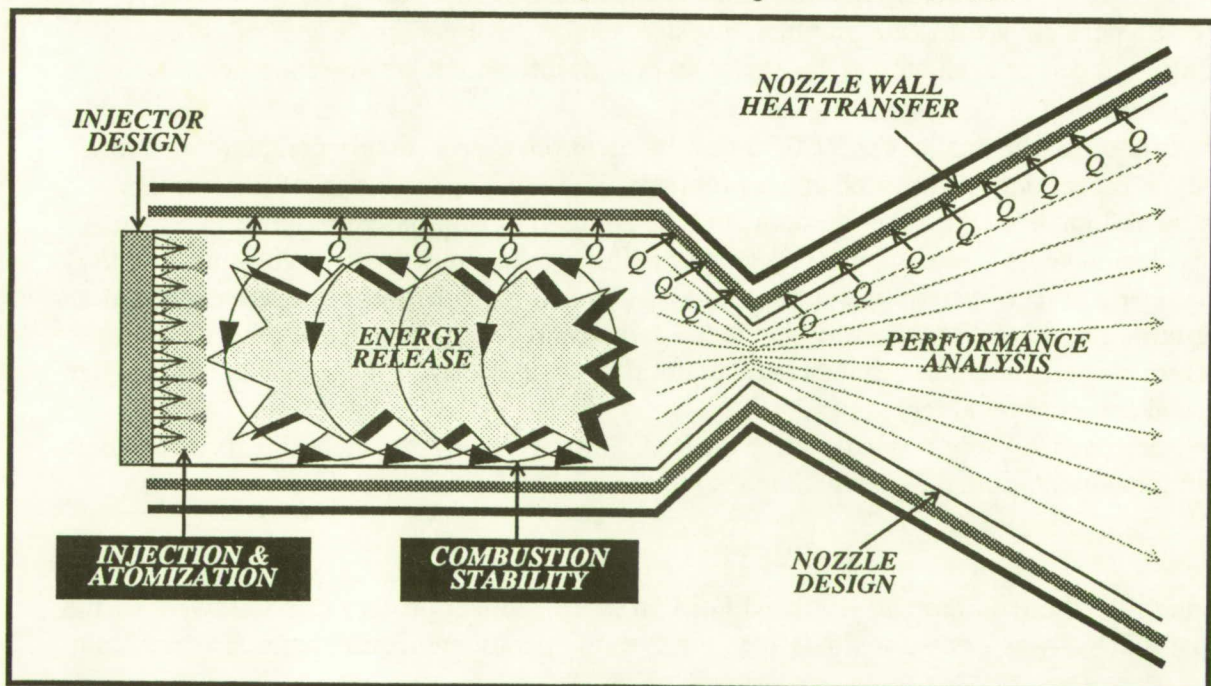
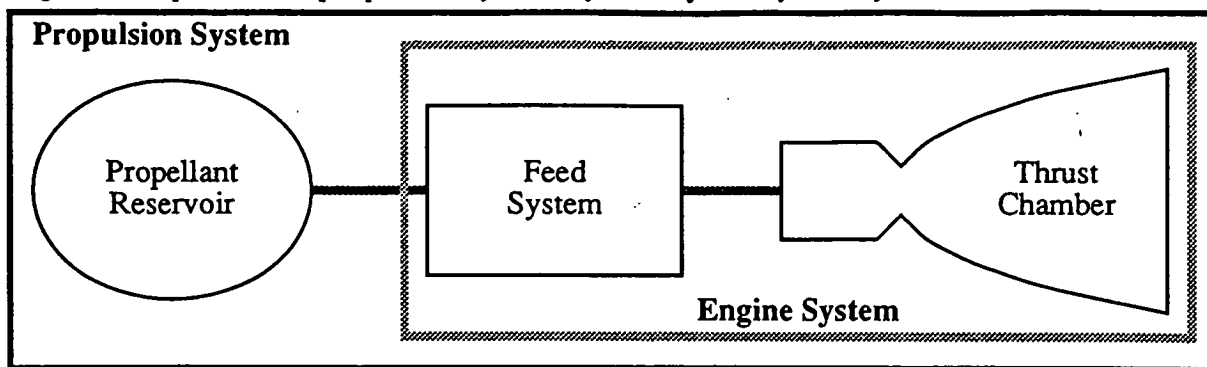


Figure 2. Liquid rocket propulsion system reference frame, from reference 2.



When the experts perform an analysis or design by themselves, they tend to resort to engineering simplifications to accomplish the portions of the analysis which lie outside their area of specialization. These simplifications are done by making use of less complex computer codes as well as generalized "rules of thumb." Expert systems can make complex codes easier to use, provide for data sharing between individual codes, and permit the interaction of codes for an iterative solution. An expert system designed to carry out a liquid rocket engine design would encourage the proper use of technically rigorous computer codes and provide expertise to a user who may not be an expert in these areas.

In 1989, development of an expert system began at the NASA Lewis Research Center (LeRC) to collect, automate, and perpetuate the existing expertise of performing a comprehensive rocket engine analysis and design. To speed development, the expert system is being built within a commercially available expert system shell. A rocket engine design "knowledgebase", consisting of numeric and symbolic data, computer programs, graphic images, and lines of code written in the Lisp computer language, is being developed. Combining the specialized rocket engine design knowledgebase with the expert system shell software functionality results in the Rocket Engine Design Expert System (REDES). Initially, REDES contained preliminary computational and design capabilities demonstrating liquid rocket engine thrust chamber analyses¹. Ultimately, REDES could perform a complete propulsion system analysis with all of the individual components being designed or evaluated at the expert level with interaction between components to achieve optimization of the system (figure 2)².

In the near-term, the goal of the REDES development program is timely computational analyses of liquid rocket engine thrust chamber problems. Through the expansion of the current computational domain of the expert system, and the addition of rule-based design capabilities, REDES will achieve its intermediate-term goal of being able to evaluate the performance of the thrust chamber and feed system (turbomachinery), as well as provide limited design capabilities. The long-term goal of the REDES program is to analyze and design a complete propulsion system, from propellant tanks to thrust chamber nozzle exit, using state-of-the-art heuristic design methods and computational tools.

The objective of this report is to describe the REDES program to date, including its design definition and implementation, development management, and technical capabilities.

SYSTEM DESIGN

To determine the requirements of the REDES program, a linear process was followed. Identifying what REDES was desired to do defined the system operational requirements. Determining

what basic functions could meet these requirements defined the system functional requirements, and a specific expert system shell was identified to meet these needs. Hardware resource requirements of the specific shell software next determined the class of computer required, and the specific hardware on which to develop the expert system was selected.

REDES' operational requirements included the abilities to: provide a simple interface between the user and the operation of available functions, analyze the performance of a liquid rocket engine, design various components of a liquid rocket engine, provide results to the user, and facilitate the integration of new analysis and design procedures.

Deciding to use an expert system shell to build REDES satisfied the last operational requirement. Expert system shells facilitate the integration of new capabilities and functions into the knowledgebase. Design features which were determined to meet the remaining system operational requirements included:

- a "point and click" style of interface, utilizing a system of overlapping image panels, menus, push-buttons, and value displays, to give REDES a simple and intuitive feel. Limited keyboard entry is necessary only to input individual parameter values.
- analyses of liquid rocket engine performance and parameters accomplished through the inclusion of a JANNAF standard computer code³ and other available programs^{4,5}.
- thrust chamber design capabilities by using independent design codes⁶ or by programming design algorithms directly into the expert system using the Lisp programming language.
- output from the analysis or design portions of REDES provided to the user through the expert system interface or in the form of graphical plots. Output datasets from each code within REDES are available to the user after a run and can be viewed using the editor within the expert system shell, or printed out using the appropriate operating system commands, outside the shell software.

These design features required a set of system functional requirements to be provided by the shell software: an extensive graphical capability to build the user interface and to display output results, the ability to interact with the computer's operating system to run performance evaluation codes, and an object oriented programming language for discrete integration of component analyses. The expert system shell chosen to manage this problem was the Knowledge Engineering Environment (KEE), available from IntelliCorp, Incorporated.

Computer hardware requirements were established based on the expert system shell software, including the amount of random access memory (RAM), disk storage space, operating system, graphics monitor, tape drive, peripherals, resident languages, and swap space. The hardware selected for the REDES development program was the model 4/110 computer from Sun Microsystems, Incorporated.

Figure 3 is a high-level diagram showing REDES' interfaces with the user, Lisp functions, the operating system, and all currently implemented computer programs.

DEVELOPMENT APPROACH

The approach taken with respect to managing the development of REDES incorporated the definition of expansion capabilities, and a prioritization scheme for implementing new features. An

important aspect of REDES' development is identifying the customers and end-users, and anticipating and meeting their needs.

Listed in table 1 are some of REDES' potential technical and functional capabilities. Some of these may require the acquisition and execution of computer codes, while others depend solely upon functions which must be programmed into the expert system shell. Capabilities of REDES can be broken down into two main categories: functional and technical. Functional capabilities provide the user a utility which assists in the operation of the expert system, but do not analyze or predict the performance of a rocket engine or any of its components. Measurement unit conversions and help screens are examples of functional capabilities. Technical capabilities can themselves be divided into two subcategories: analysis and design. Analysis capabilities include performance evaluation computer codes which REDES autonomously runs from a user provided design. Design capabilities include functions which perform an actual design that conforms to a set of user provided requirements.

In order to determine which capability receives development priority, an "as needed" implementation policy was adopted. After base technical analytical capabilities within REDES were implemented, REDES was used as an analytical study "work horse". Members of the Space Propulsion Technology Division (SPTD) at NASA LeRC supplied several problems to REDES developers. Functions were written to automate the desired analytical studies. These functions take advantage of REDES' computational and functional assets, and perform the data analysis steps required for a computational study. In this way, new capability prioritization has been based on current problem needs.

As previously mentioned, the near-term goal of REDES was defined as timely computational analyses of liquid rocket engine thrust chamber problems. Meeting existing computational needs prioritizes the implementation of REDES' new technical and functional capabilities.

Figure 3. Interfacing between REDES and the computer programs is achieved through the use of operating system calls made by LISP functions

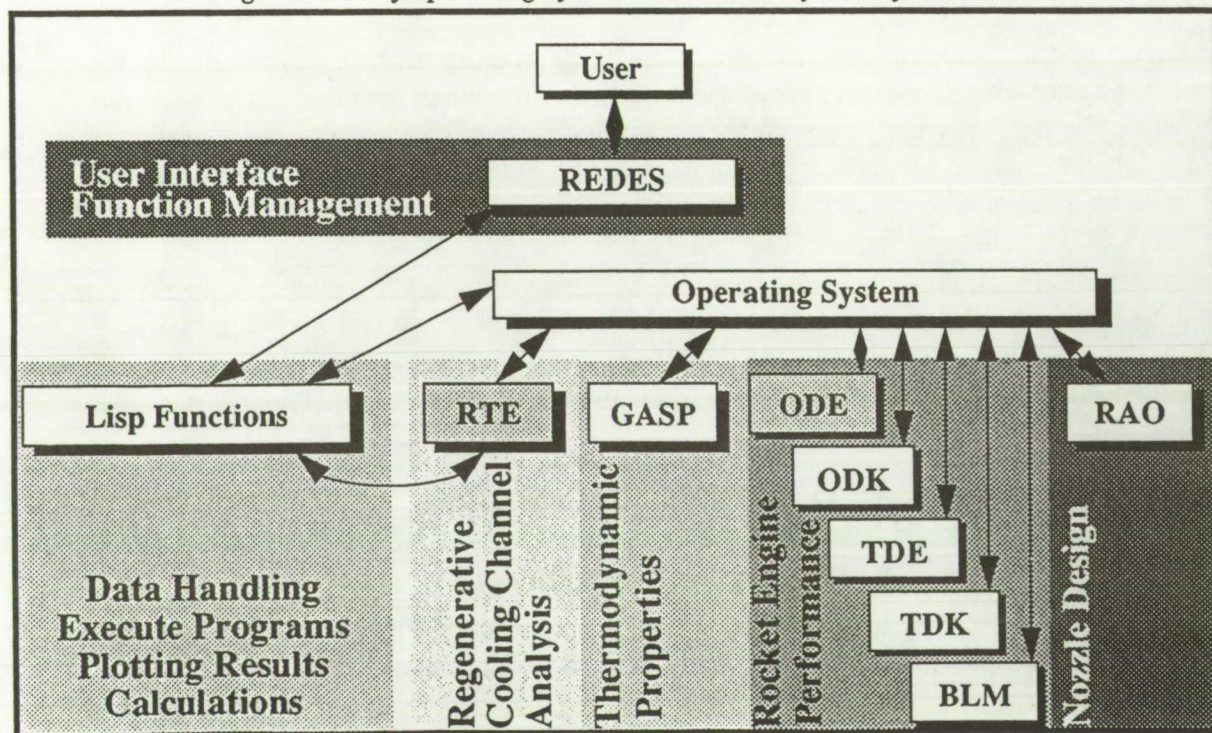


Table 1. Listing of REDES' possible technical and functional capabilities.

<u>Technical Capabilities</u>		<u>Functional Capabilities</u>
Add Combustion Stability Code	Analysis ↑ ↓	Add REDES Start-up Sequence
Add Atomization/Vaporization Code		Add Help Control Panel
Add New Injector Designs	Design ↑ ↓	Add Program Sequencing
Perform Chamber Life Calculations		Add Auto-Demo
Add Machine Design Optimizations		Add Graphical Data Input
Design Heat Sink Hardware		Add Coordinate Sharing
More Δp Calculation Schemes		Sophisticated Error Trapping
Regenerative Cooling Channel Design		

CAPABILITIES

REDES' current computational capabilities for each of the disciplines shown in figure 1 is described below. Figure 3 shows the names of individual codes or modules which are used to evaluate performance of the thrust chamber. Capabilities of the expert system shell and REDES allow any computer programs to be linked to one another, allowing for iterative, interactive solutions to rocket engine problems.

Injector Design - Computation of thermodynamic properties of propellants is computed using a fluid properties program named GASP⁴. Properties of propellants which GASP cannot handle are computed using simplified relationships. Design is currently limited to a simplified algorithm for coaxial injector elements, determining the number and location of the elements on the injector face.

Energy Release and Performance Analysis - A JANNAF standard computer code, called the Two Dimensional Kinetics (TDK) reference computer program³ is used for both of these disciplines. TDK is a collection of computational modules which allow the user to select which physical phenomena should be considered in the analysis. Computer modules included in TDK which are currently a part of REDES are: One Dimensional Equilibrium (ODE), Two Dimensional Equilibrium (TDE), One Dimensional Kinetics (ODK), Two Dimensional Kinetics (TDK), and the Boundary Layer Module (BLM). Together, these programs can evaluate the performance of the combustion chamber, throat, and supersonic nozzle regions. Table 2 gives the TDK fuel and oxidizer options available within REDES.

Nozzle Wall Heat Transfer - REDES can analyze nozzle wall heat transfer cases including an adiabatic or a regeneratively cooled wall. TDK is used to determine performance of the thrust chamber with an adiabatic nozzle wall. Regenerative cooling channels are analyzed within REDES with the Rocket Thermal Evaluation (RTE)

Table 2. List of TDK fuel and oxidizer options available within REDES.

Fuels: H ₂ , CH ₄ , MMH, RP-1, UDMH, N ₂ H ₄
Oxidizers: O ₂ , H ₂ O ₂ , F ₂ , HNO ₃ , N ₂ O ₄ , Air

Table 3. Specifications identifying engines investigated in the REDES and ASES analyses.

Case	1	2	3		4			5		
Missions	LC	LM	LTV	LEV	LTV	LEV1	LEV2	MTV	MEV1	MEV2
Thrust/Engine	20K	20K	20K	20K	20K	10K	10K	34K	34K	34K
No. Engines	2	4	4	4	4	3	3	3	4	2
Core Diameter	15 ft	15ft	15ft	25ft	15ft	15ft	25ft	5m	7m	5m
LC≡Lunar Cargo					LM≡Lunar Manned					
LTV≡Lunar Transfer Vehicle					LEV≡Lunar Excursion Vehicle					
MTV≡Mars Transfer Vehicle					MEV≡Mars Excursion Vehicle					

code⁵. RTE can be coupled with other codes to allow analytical interactivity. For example, for given constant chamber conditions, RTE solutions can be iteratively computed to determine the coolant channel inlet temperature and pressure which result in the desired chamber conditions.

Nozzle Design - To determine the contour of the supersonic nozzle, REDES makes use of the many nozzle contour option available within TDK as well as the RAO⁶ nozzle design code. A nozzle contour can be computed as a preliminary step for any other analysis performed by REDES.

Two disciplines, "Injection & Atomization" and "Combustion Stability", are shown in figure 1 as darkened boxes. These disciplines are currently not included in REDES.

Regions of the rocket engine for which a frame structure and computational capability currently exists include the thrust chamber and the regenerative cooling channel portion of the feed system. Development of the frame structure for the feed system and turbomachinery portion of the propulsion system in REDES has begun, but no analytical capabilities have been implemented.

SAMPLE APPLICATION OF REDES

REDES was used to conduct studies such as the thrust dependent engine sizing analysis described below. An advanced space engine sizing (ASES) analysis, performed using simplified analysis procedures, was rerun using REDES' engine sizing function and results were compared.

The propulsion systems investigated in the ASES and REDES analyses were categorized into five different cases, differentiated by the mission, number of engines, thrust per engine, and propulsive core diameter of each vehicle (table 3). Performance of each engine was computed for three chamber pressures.

In the ASES analysis, an ODE thrust coefficient and an assumed value of thrust was used to calculate values of throat radius, expansion ratio, and nozzle length to match the propulsive core diameter constraint. A simplifying assumption that thrust levels remained constant for nozzles of any length was adopted. In reality, however, two-dimensional, chemical kinetic, and boundary layer losses cause the thrust level to vary from the starting value if the nozzle length is changed. These real effects were taken into account in the REDES analysis to calculate the thrust decrement value. REDES iteratively increased the throat radius value until the calculated thrust value, including the real effects thrust decrement, matched the desired value.

Engine geometric and operating condition data, given in table 4, were used in the REDES study. REDES held constant the thrust level, chamber pressure, percentage of a 15° cone, and exit

Table 4. Sample input geometry and operating conditions for the REDES analysis.

Throat Radius (in) =	1.633	O/F =	5.035
Chamber Radius (in.) =	1.7899	Fuel = H ₂ : T _{inj, fu} =	20.56 °K
Upstream Radius of Curvature =	2.0623	Oxidizer= O ₂ : T _{inj, ox} =	90.11 °K
Downstream Radius of Curvature =	0.1900		
Upstream Tangent Angle =	26.25°		
Downstream Tangent Angle =	32.00°		

radius. Outputs included values of throat radius, expansion ratio, nozzle length, and specific impulse.

A flowchart for the REDES engine sizing function is shown in figure 4. As an initial estimate of the throat radius, r_t , the One Dimensional Equilibrium (ODE) computer code was run and the ODE value for thrust coefficient, C_F , was used in equation 1. This throat radius was then used in the rigorous JANNAF methodology analysis to determine the thrust level, F_{Calc} , using the calculated thrust coefficient, $C_{F,Calc}$, after two-dimensional, kinetic, and boundary layer effects had been accounted for. If the thrust computed by the analysis (given in equation 2) was not equal to the target thrust level, F_{Target} , within a given tolerance limit, a new throat radius was calculated using F_{Target} , chamber pressure, p_c , and $C_{F,Calc}$, again using equation 1. This process repeated until the target thrust level was within the tolerance limit.

$$r_t = \sqrt{\frac{F_{Target}}{C_F p_c \pi}} \quad (1)$$

$$F_{Calc} = C_{F,Calc} \pi r_t^2 p_c \quad (2)$$

Figure 4. Flowchart of REDES thrust dependent engine sizing function.

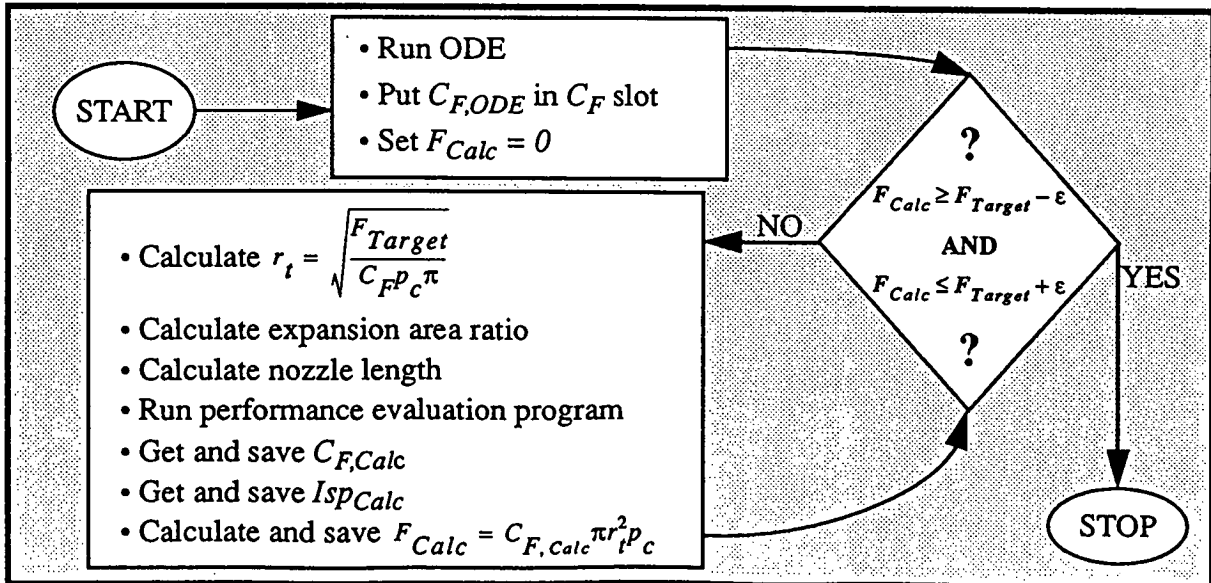
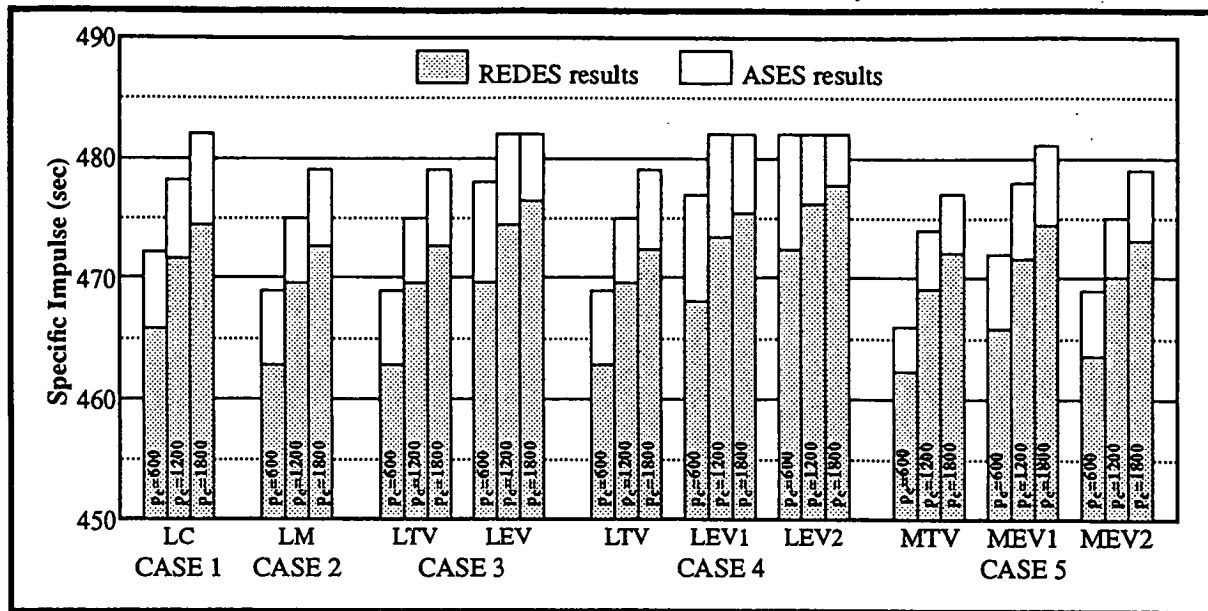


Figure 5. Isp comparison between the REDES and the ASES analyses.



Implementation of the JANNAF methodology in predicting the rocket engine performance included adherence to two points concerning the input data: both propellants were injected into the thrust chamber in the liquid state, and the boundary layer analysis was performed on an adiabatic nozzle wall, thereby reducing the non-boundary layer heat losses to zero.

Results from the analyses are shown in figure 5. ASES performance results (white bars) were consistently higher than REDES results (gray bars), highlighting the conclusion that simplified analyses can produce overly optimistic answers. In absolute terms of calculated specific impulse, the ASES analysis' values were an average of 6.4 seconds higher ($\approx 1.5\%$) than the REDES results. Simplified analyses can even lead to bad results, as shown in case 4 where the difference between the two analyses' results was 9.83 seconds. The greatest discrepancies between Isp differences at low (600 psia) and high (1800 psia) chamber pressure values occurred in the seventh set of results where ASES predicted no performance gain with an increase of chamber pressure, while REDES calculated a 5.6 second benefit.

CONCLUDING REMARKS

An overview of the Rocket Engine Design Expert System (REDES) has been presented, including: a description of REDES' computation domain and the expert system being developed, the system requirements, a design overview, how the program development is being managed, and REDES' current capabilities.

REDES currently provides the rigorous JANNAF methodology analysis of the liquid rocket engine thrust chamber. Computer programs included in REDES are executed through automated input dataset creation, program execution, and automatic collection of results from the output dataset.

Computational studies, such as the thrust dependent engine sizing analysis, have been performed for the Space Propulsion Technology Division at the NASA Lewis Research Center. These have shown REDES' capability to implement and perform timely customized computational studies with a high level of technical rigor. The example analysis described in this report shows

how over-simplified analyses can lead to over-optimistic results, bad answers, and misleading conclusions.

Meeting existing computational needs prioritizes the implementation of REDES' new technical and functional capabilities. Requests for computational studies from members of the liquid rocket engine community would be used to prioritize the implementation of future REDES capabilities.

REDES is planned to be made publicly available. However, since it has been developed in a commercial shell, it will be necessary for potential end-users to obtain a run-time or development license for KEE from IntelliCorp, Incorporated, to have access to the hardware and software resources which are required to run KEE and REDES, and make a written request to the author for a copy of REDES. After these requirements have been fulfilled, REDES would then be delivered to the requester with no expressed or written guarantees or warranties. REDES end-users could communicate REDES bug reports and desired additions to the author by phone and in writing. Updated versions of REDES would be distributed as they became available.

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